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Evaluations of Global Wind Prediction at Fleet Numerical Meteorology and Oceanography Center: from the Perspective of a Wave Modeler

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14. ABSTRACT

This study describes the validation of winds fields used in a companion study ("Evaluation of global wave prediction at Fleet Numerical Meteorology and Oceanography Center," submitted for review). During this validation, it is found that conventional methods of estimating the distribution of bias across wind speeds can produce widely misleading conclusions. This is demonstrated, and a simple solution (histogram comparisons without geographic interpolation) is presented.

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Abstract

This study describes the validation of winds fields used in a companion study ("Evaluations of global wave prediction at Fleet Numerical Meteorology and Oceanography Center", submitted for review). During this validation, it is found that conventional methods of estimating the distribution of bias across wind speeds can produce widely misleading conclusions. This is demonstrated, and a simple solution (histogram comparisons without geographic interpolation) is presented.

Introduction

The NOGAPS (Hogan and Rosmond 1991) wind fields, NOGAPS/QuikSCAT wind fields, and the wave model hindcasts are introduced in the paper "Evaluations of global wave prediction at Fleet Numerical Meteorology and Oceanography Center", submitted for review. Related manuscripts are included in the References section of this report.

Wind field Validation

1 Ground Truth

The wind fields used to force the hindcasts are compared to in situ wind data. National Data Buoy Center (NDBC) buoys are selected from the general population of NDBC buoys with preference given to buoys further offshore, as these are expected to be more representative of the open ocean, where the vast majority of wave energy is generated. Seven buoys each in the Pacific Ocean (46066, 46035, 46001, 46005, 46002, 46006, 46059) and Atlantic Ocean (44011, 44005, 44018, 44008, 44004, 41001, 41002) were used. Their locations are shown in Fig. 1. Also shown in Fig. 1 is the spatial distribution of the fractions of occurrence of gale force winds ($U_{10} > 15$ m/s) during the winter 2002/2003 hindcast period (in the blended NOGAPS/QuikSCAT wind fields, tabulated at three hour intervals) in the north Pacific and north Atlantic. The areas with high occurrence of strong winds may be considered the predominant swell generation regions during the period. It is apparent from the figure that the buoy network is reasonable—though far from ideal—for validating winds in the predominant swell generation regions: the buoys are located in moderately active areas. In this validation, buoy wind speeds are converted to 10 m elevation assuming neutral stratification. Except where stated otherwise, model forcing fields are collocated with the buoys via tri-linear interpolation (two space coordinates plus time coordinate).

In the validations to follow, the accuracy of our "ground truth" is an important consideration. Hamilton (1980) and Gilhousen (1987) report typical RMS (thus not necessarily systematic bias) wind speed errors (in buoy data) as being 1.0 ms^{-1} or better. Yet it is expected that buoy wind speed measurements are less accurate in high winds due to the movement of the buoys in corresponding high seas (Ebuchi et al. 2002), as well as wind profile distortion by large waves (Large et al. 1995); only very limited validation of buoy anemometer measurements against fixed platform measurements in high winds have been performed. Despite these shortcomings, the buoy-mounted anemometer

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measurements are our best option for ground-truth, as they are the most direct open ocean wind measurements available to us.

Data were not available from all buoys during all time periods of interest. Where data did exist, they were compared to corresponding values in the model forcing fields. The wind fields were interpolated to the buoy locations as appropriate. For each forcing type and hindcast period (four combinations total), all collocated points were combined into a conventional scatter-plot comparison (these plots can be obtained from the author; they are not included here).

2 Results

Validation comparisons were created for both hindcast periods and for three wind forcing field types: 1) NOGAPS, 2) NOGAPS blended with QuikSCAT measurements (quality control flagged QuikSCAT measurements included), and 3) NOGAPS blended with QuikSCAT measurements (quality control flagged QuikSCAT measurements omitted). The latter are referred to as "filtered" NOGAPS/QuikSCAT fields below. Both "filtered" and "unfiltered" fields were included in the validation to quantify the impact of including flagged measurements and to subsequently decide which to use in the wave model hindcasts.

The traditional method of wind field validation is to present scatter plot comparisons of measurements against collocated wind field values, along with statistics such as RMS error, bias, and regression parameters. The RMS error and bias unfortunately are of limited value to this study, since they do not provide information regarding the error at different wind speeds, which is crucial here because of the obvious increased sensitivity of a wave model to higher wind speeds. The regression parameters do contain this sort of information, but as will be demonstrated below, various factors can lead to widely misleading regressions. Much of the focus of this validation will be on addressing these problems.

Due to space limitations, we cannot present all results here. Figure 2(a,b) shows some of the results from the validation for the 2001/2002 filtered, blended NOGAPS/QuikSCAT forcing fields. The apparent positive bias at low wind speeds is probably due to the nature of the comparison: it is well known that comparison of scalar wind speeds tends to suggest spurious relations near the origin of a scatter plot (i.e. at low wind speeds); see e.g. Freilich (1997), Dickenson et al. (2001), Ebuchi et al. (2002). Such spurious relations will obviously tend to skew linear regressions of scatter plots. These two plots suggest that at moderate to high wind speeds (5-22 ms^{-1}), the mean error (i.e. bias) of the wind field is relatively slight (less than 1 ms^{-1}) and is negative at higher wind speeds.

During both time intervals, the RMS error—calculated from the entire wind speed range—of the filtered NOGAPS/QuikSCAT fields is greater than the RMS error of the NOGAPS fields: 2.12 ms^{-1} vs. 1.96 ms^{-1} in the 2001/2002 period and 2.17 ms^{-1} vs. 1.99 ms^{-1} during the 2002/2003 period. This is not surprising, since the atmospheric model is expected to be fairly accurate predicting low and moderate wind speeds, whereas the process of blending in QuikSCAT measurements introduces sampling error (e.g. Schlax et al. 2001), which tends to be random.

The comparison method of Fig. 2 (scatter plots and binning by buoy wind speed) is fairly mainstream, having been used by others such as Ebuchi et al. (2002), yet it is possible to make some additional comparison more pertinent to wave model sensitivity.

Focusing on the mean error of Fig 2b, it can be argued that the practical impact of a wind speed "bin" should be weighted according to the population of that bin. Further the disproportionate impact that high wind speeds have on wave climate should also be recognized. We can do this by weighting each wind speed bin according to the wave energy that it might produce. For this purpose, we use the wave height calculated from the so-called "Pierson-Moskowitz (PM) spectrum" (Pierson and Moskowitz 1964)[1]. This can be interpreted as a weighting according to the square of the wind speed. The mean errors for the three winter 2001/2002 forcing fields, weighted in this manner, are shown in Figure 3. This comparison suggests that overall all bias is smallest in the NOGAPS fields blended with unfiltered QuikSCAT data.

There is another qualification that must be mentioned. During the validation process, it was noticed that bias comparisons such as Fig. 3 could be misleading at the higher wind speeds. This effect has, in fact, been noticed by others. Freilich and Dunbar (1999) note that apparent negative bias at high wind speeds may "be the result of binning on buoy wind speeds....Wentz et al. (1984) and Chelton and Wentz (1986) showed that apparent underpredictions in high wind scatter plots were expected if the buoy measurements had random errors." [The topic is also discussed by Tolman (1998).] Note that this spurious effect will tend to have a similar effect on the slope of scatter plot regressions as does the low wind speed problem mentioned above. Acknowledging that this effect exists, it is reasonable to speculate that the winter 2001/2002 blended NOGAPS/QuikSCAT wind forcing field may actually have a slight positive bias at high wind speeds rather than the slight negative bias apparent here, and the negative bias in the 2001/2002 NOGAPS wind forcing field at high wind speeds, though significant, is probably exaggerated in this comparison.

Fortunately, we have another way to present the collocation comparisons which does not share this problem: to create a histogram of all buoy measurements and compare to a histogram of the collocated wind forcing field values. Though this does not give any indication of random errors (e.g. errors resulting from a misplaced cyclone), it does tell us much about systematic bias (e.g. errors from consistently underpredicted cyclone strength), and random error in the buoy data should not affect our interpretation. Figure 4 shows such a comparison for the winter 2001/2002 period, with the number of occurrences weighted by the PM wave height, as in Fig. 3. This comparison (Fig. 4) tends to favor the blended NOGAPS/QuikSCAT wind fields created with filtered QuikSCAT measurements. The unfiltered NOGAPS/QuikSCAT fields show a positive bias at the higher wind speeds.

To summarize, the merits (with regard to wind speed bias) of using or omitting quality-control flagged QuikSCAT data depends on the method of validation. If we assume that random error in the buoy data is negligible[2], we may bin wind speed according to buoy wind speeds. This comparison supports using flagged data (Fig. 3). On

[1] Though lacking the sophistication of a full wave model, the PM spectrum suits our purposes because it is simple and widely known. The PM spectrum gives us a simple relation between wind speed and wave height under a number of large assumptions, one being that the local wave condition is "fully developed". This implies that the wave state is as it would be if the wind has been blowing at the same speed and direction for an infinite duration over an infinite fetch. Here, we use the form of the PM spectrum given by Komen et al. (1984).

[2] Buoy wind speeds are typically calculated on 8-minute averages. This would seem to support the argument that random error is small.

the other hand, histogram comparisons support omitting flagged data (Fig. 4). Since the latter is much less sensitive to random error, we choose to omit flagged data.
Thus, the unfiltered fields are dismissed as a candidate for hindcast forcing and are not included in the additional validation comparisons below.

Yet, that is not the end of the story! The act of geographic interpolation to collocate forcing fields with buoy location is expected to have a smoothing effect in cases where the signals (e.g. those due to cold fronts) in a field of 10 m wind speeds are not well described by a model grid[3]. Again, the histogram approach gives us an advantage: slight, random shifts in individual buoy locations are not expected to have a marked effect on the histogram created from all 14 buoys. Thus, we can skip interpolation by simply taking model output at the model node nearest each buoy and considering it collocated (i.e. nearest neighbor collocation). This experiment yields histograms of different shape (for example, with nearest neighbor comparison, note the positive bias that is more pronounced in the filtered NOGAPS/QuikSCAT fields in the 15-20ms^{-1} range). Comparison via the nearest neighbor approach is expected to be less sensitive to spurious effect.

Figure 5(a,b) shows the results for the 2001/2002 and 2002/2003 periods. These results can be distilled further by considering the mismatch (forcing field histogram vs. buoy histogram) in individual wind speed bins (Table 1). With the histogram mismatch as a metric of forcing field bias, these comparisons suggest the following:

1) Of the four forcing fields, the 2001/2002 NOGAPS has the most severe bias.
2) The 2002/2003 NOGAPS field has the smallest bias.
3) The apparent bias in the NOGAPS fields (for both time periods) is expected to result in an underprediction of wave energy by a "perfect" wave model. The negative bias is primarily at 10m wind speeds greater than 12 ms^{-1}.
4) The apparent bias in the blended NOGAPS/QuikSCAT fields is expected to result in an overprediction of wave energy by a "perfect" wave model. The positive bias is primarily at 10m wind speeds greater than 15 ms^{-1}.
5) The apparent bias in the blended NOGAPS/QuikSCAT fields is remarkably similar for the two time periods. This might be taken as an indication of the robustness of the method.

Note that we do not know from this comparison how much of the error in the NOGAPS/QuikSCAT wind fields is from NOGAPS and how much is from the QuikSCAT measurements. However, the literature gives us some insight into this. The mission requirements for QuikSCAT are to achieve accuracy within ±2 ms^{-1} for $3\,\mathrm{ms}^{-1} < U_{10} < 20\,\mathrm{ms}^{-1}$ and ±10% for $20\,\mathrm{ms}^{-1} < U_{10} < 30\,\mathrm{ms}^{-1}$ (PODAAC 2001). Ebuchi et al. (2002) evaluated the accuracy of the L2B QuikSCAT data (with data flagged for quality control removed) using a large number of offshore buoy measurements as ground truth. They concluded that the mission (i.e. accuracy) requirements are satisfied. Using comparisons similar to Fig. 2, they find no significant dependency on wind speed, except at high wind speeds ($U_{10} > 15\,\mathrm{ms}^{-1}$), where there is a slight positive bias.

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[3] Imagine the extreme case where the time series at one node in a one-dimensional model is a sine wave, and the time series at a neighboring node is the same signal, except with a phase shift (say, a sine wave offset by half a cycle). Interpolation to an intermediate location will yield a damped time series.

Conclusions

Using direct validation of NOGAPS analyses against buoy data, it is shown herein that the negative bias at high wind speeds is much reduced during the winter of 2002/2003, compared to the previous winter.

During the validation of wind fields, it is observed that traditional metrics such as wind speed bias and RMS error are of limited value in the context of wave modeling, since they do not provide information regarding the error at different wind speeds, which is crucial because of the obvious increased sensitivity of a wave model to higher wind speeds. Further, traditional methods of validation (e.g. scatter plot diagrams) produce apparent bias at low and high wind speeds which are likely spurious. For evaluation of wind speed bias, this can be circumvented by comparing histograms of collocated wind speeds. The method of collocation also is shown to have a strong influence on the apparent bias. Further, we show how a simple modification of validation plots—weighting according to wind speed—allow us to better quantify the expected impact of wind speed bias on wave model results.

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Table 1. Statistics derived from wind field validation. The first statistic is simple RMS error from the scatter plot of Fig. 2. The other two statistics are from the histograms of Fig. 5 (histograms of the buoy measurements and collocated wind forcing field values, weighted by population and Pierson-Moskowitz wave height, collocated via nearest neighbor method). The two forcing fields are NOGAPS fields and combined NOGAPS/QuikSCAT fields (flagged QuikSCAT measurements filtered out). Here, Δ_i is the buoy/model mismatch in the histogram at an individual wind speed bin *i*. Since the population of collocated point differ in the two hindcasts (due to availability of buoy data), these results have been normalized by the total population.

Hindcast	Field	RMS error (ms^{-1})	$\sum_{i=1}^{n} \Delta_i$ (m)	$\sum_{i=1}^{n} \lvert\Delta_i\rvert$ (m)
2001/2002	NOGAPS	1.96	-0.205	0.490
	NOGAPS/QuikSCAT	2.12	+0.172	0.208
2002/2003	NOGAPS	1.99	-0.060	0.193
	NOGAPS/QuikSCAT	2.17	+0.169	0.219

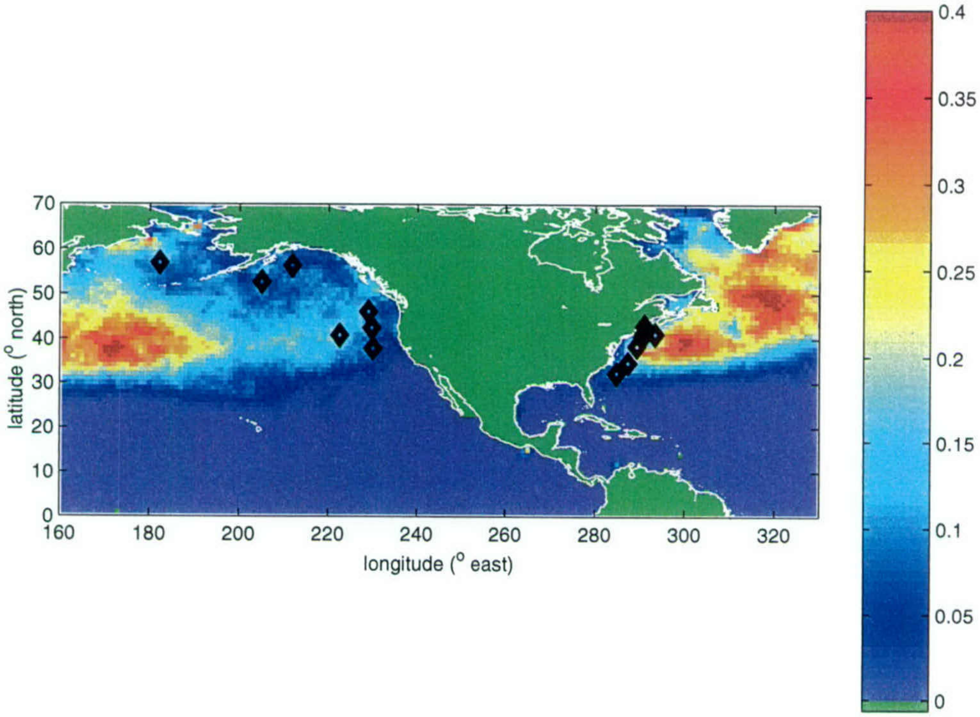

Figure 1. Locations of buoys used in comparisons to wind fields used as wave model input are shown. Color shading indicates the fraction of occurrence of gale force winds ($U_{10} > 15$ m/s) during the winter 2002/2003 hindcast period (in the blended NOGAPS/QuikSCAT wind fields). Areas with high fraction of occurrence can be considered the primary regions of swell generation in during the period.

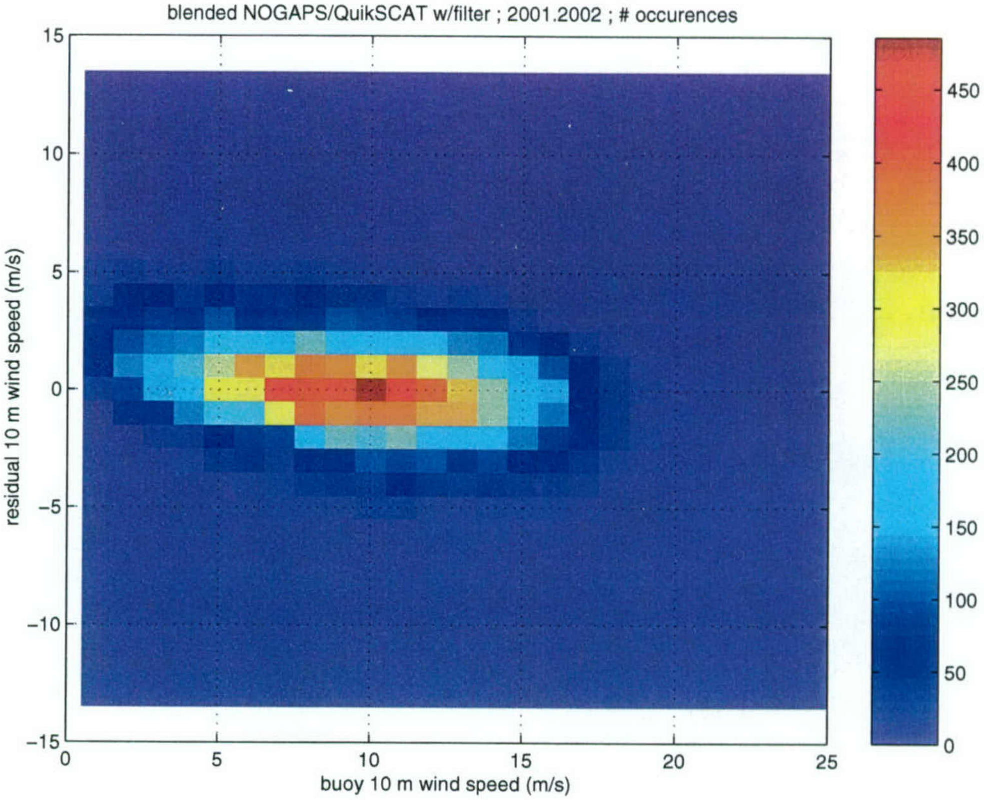

Figure 2a. Validation plot for the filtered, blended NOGAPS/QuikSCAT forcing wind field for the 2001/2002 hindcast. Color shading indicates the number of occurrences in 1 $ms^{-1} \times 1$ ms^{-1} bins. The horizontal axis is the buoy 10 m wind speed. The vertical axis is the residual wind speed, calculated as the difference between the collocated forcing field wind speed and the buoy wind speed. This comparison—and all other wind field comparisons herein—are obtained using collocations with data from 14 buoys.

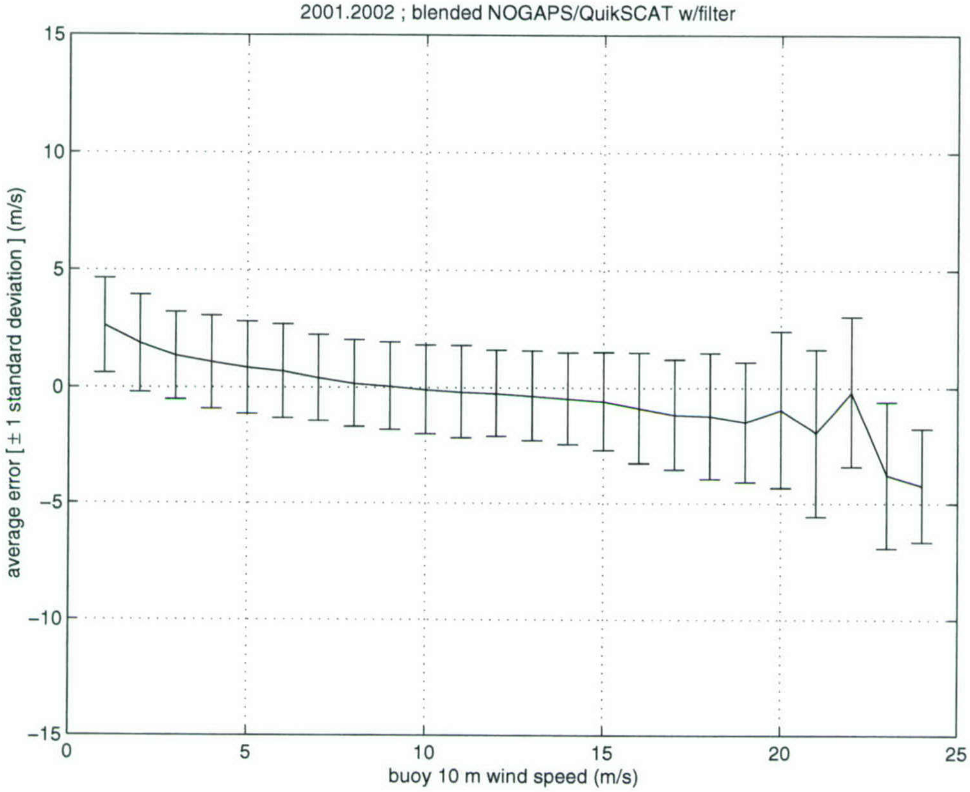

Figure 2b. Validation plot for the filtered, blended NOGAPS/QuikSCAT forcing wind field for the 2001/2002 hindcast. Individual errors, calculated as the difference between collocated buoy measurements and wind forcing field values, have been binned according to the buoy 10 wind speed (in 1 ms^{-1} bins). The mean error for each bin is indicated by the non-vertical line and the standard deviations are indicated with vertical lines (±1 standard deviation).

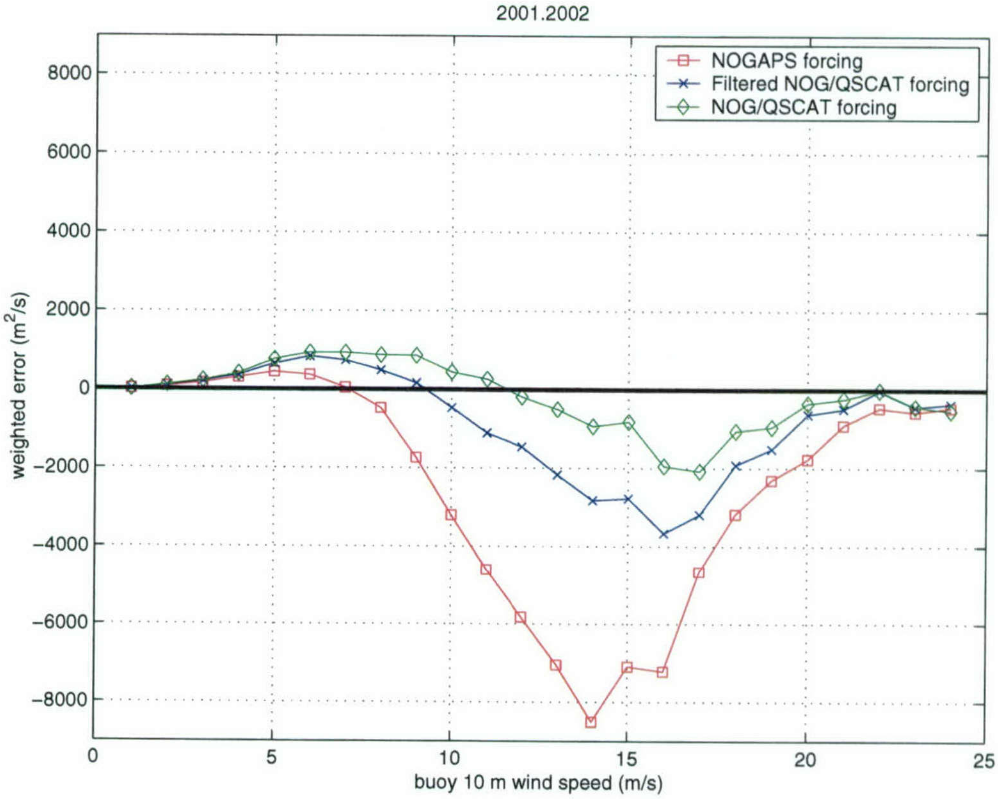

Figure 3. Mean error for the winter 2001/2002 wind fields, binned according to buoy wind speed and weighted by population and Pierson-Moskowitz wave height (see text). The three forcing fields shown are: NOGAPS fields, combined NOGAPS/QuikSCAT fields (flagged QuikSCAT measurements filtered out), combined NOGAPS/QuikSCAT fields (unfiltered).

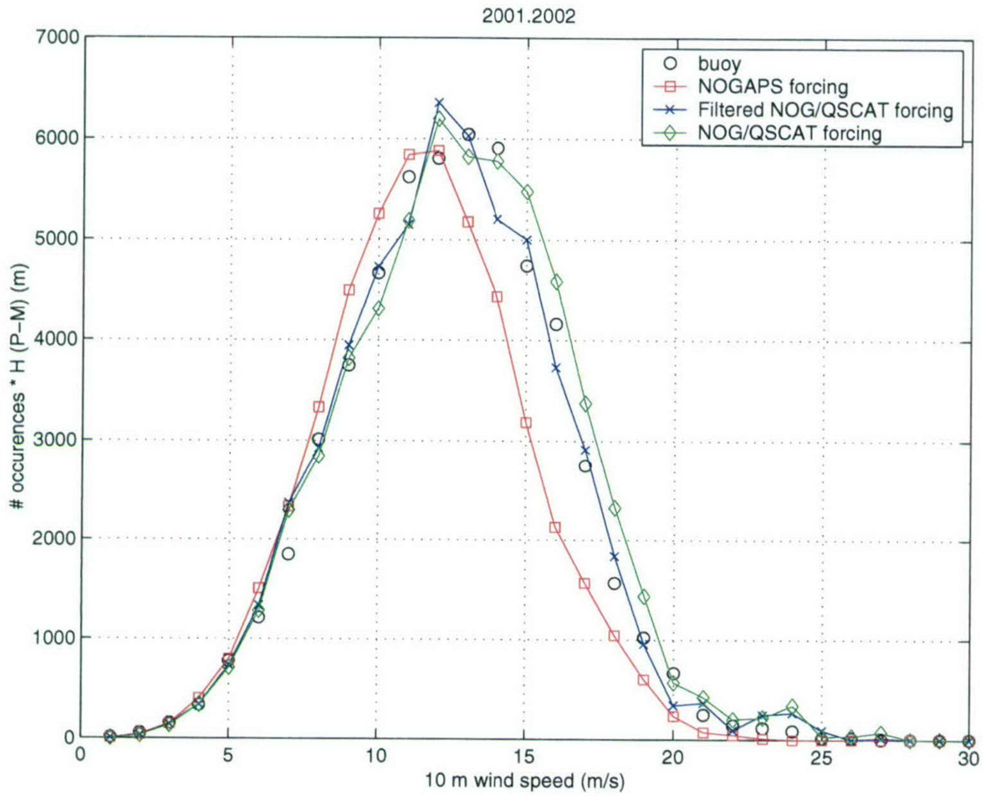

Figure 4. Histograms for the buoy measurements and collocated wind forcing field values, weighted by population and Pierson-Moskowitz wave height (see text). The three forcing fields shown are: NOGAPS fields, combined NOGAPS/QuikSCAT fields (flagged QuikSCAT measurements filtered out), combined NOGAPS/QuikSCAT fields (unfiltered). The winter 2001/2002 result is shown here. In this comparison, wind field values have been determined at buoy locations using bilinear interpolation.

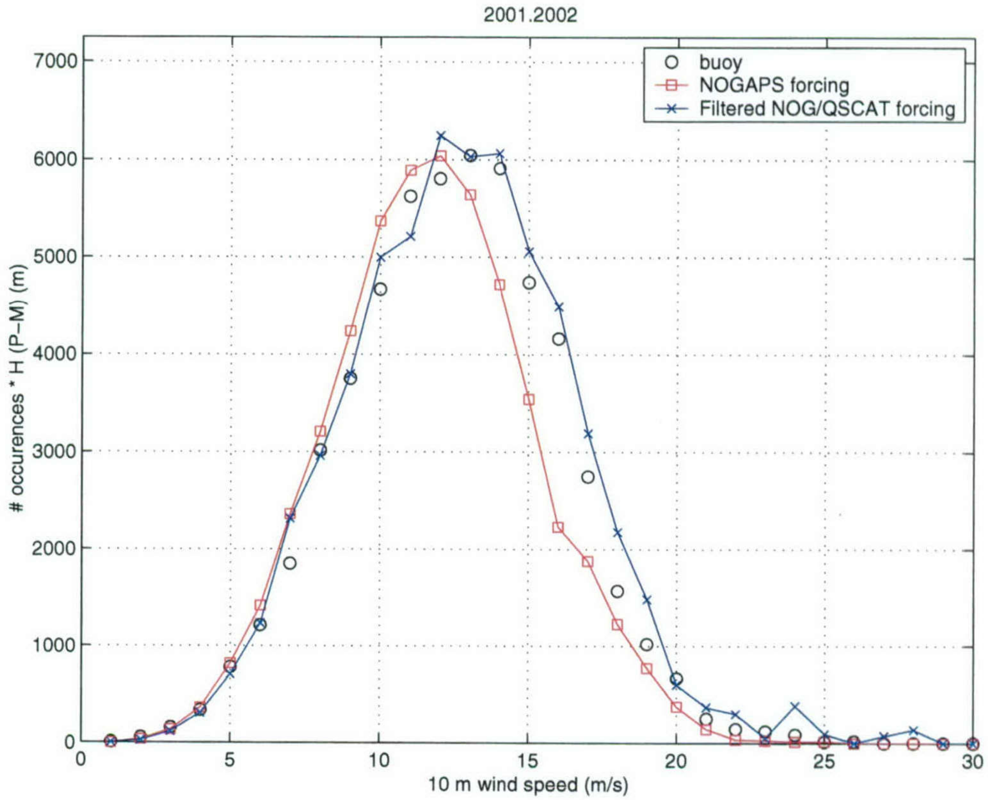

Fig. 5. Histograms for the buoy measurements and collocated wind forcing field values, weighted by population and Pierson-Moskowitz wave height (see text). The two forcing fields shown are NOGAPS fields and combined NOGAPS/QuikSCAT fields (flagged QuikSCAT measurements filtered out). In this comparison, wind field values have been determined at buoy locations by using the value in the nearest model node (*not* bilinear interpolation, as was used in Fig. 5).

Fig 5a. Winter 2001/2002 result

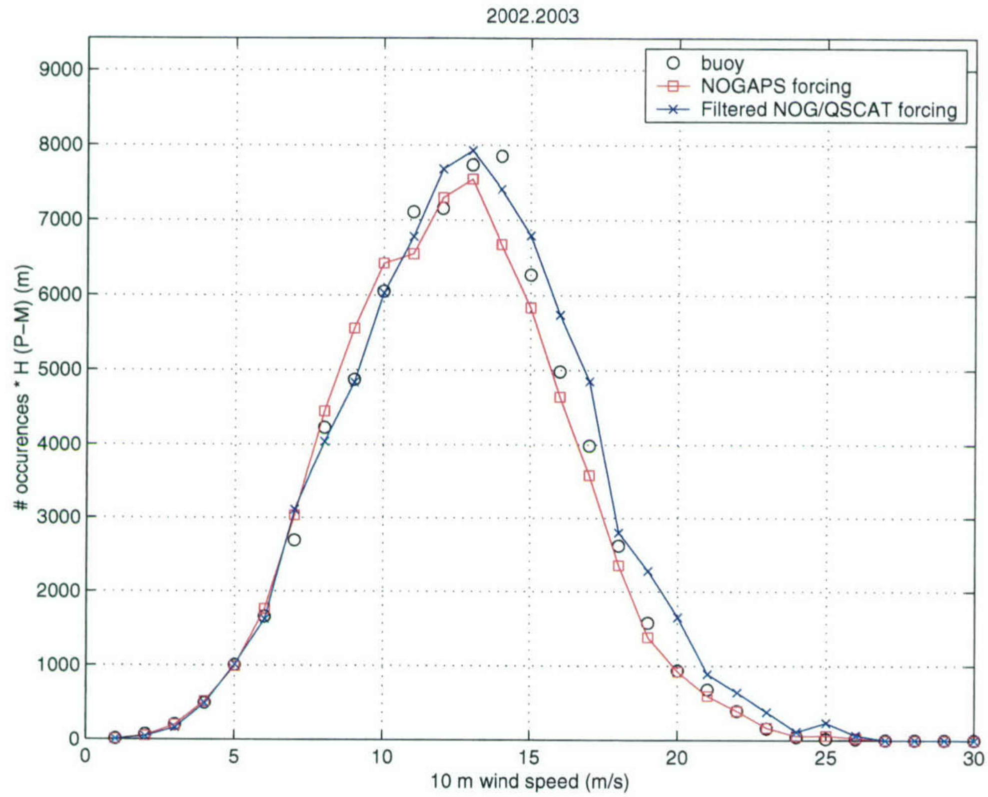

Fig 5b. Winter 2002/2003 result

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